Interstellar Dust and the H_2 Molecule

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NEARLY 20 YEARS AGO van de Hulst stated that the formation of molecular hydrogen occurs on the surfaces of the interstellar grains. (See ref. 1.) In the last years several authors discussed the problem of the interstellar abundance of the H_2 molecule. (See refs. 2 to 9.) They all found that the percentage of the molecular hydrogen in the interstellar gas probably is much larger than had been thought in the past and that the essential mechanism of H_2 formation is the formation on the particle surfaces. Therefore, the formation rate of interstellar H_2 is a function of the area of the grain surface per unit volume, which is dependent on the average radius of the grains $\bar{a}$, on the number of dust particles per unit volume $N(\bar{a})$, and on the distribution function of the particle radii. The formation rate is determined by the density of the atomic hydrogen n_H and the temperature of the interstellar gas T_{gas}. Finally, the formation rate of H_2 depends on the probability π that an impinging hydrogen atom on a grain joins with another hydrogen atom to form a molecule. The formation rate of H_2 may be written as

$$\frac{dn_{H_2}}{dt} \approx n_H^2 \bar{a}^2 N(\bar{a}) k T_{gas}^{1/2} \pi \tag{1}$$

Here k is a factor characterizing the distribution function of the particle radii. It is seen from equation (1) that the formation rate of H_2 is very sensitive to the average radius of the grains. In other words, the abundance of interstellar H_2 will be different for classical and Platt particles. This is valid since $N(\bar{a})$ for the two types of dust particles is nearly of the same order. In figure 1, the dependence of the portion of the interstellar H_2 on the whole hydrogen density in interstellar space is shown for classical grains and Platt particles. The computations were made for different values of the probability π and a temperature of the interstellar gas of 100° K. Also shown is the abundance if the formation occurs in reactions of hydrogen with the H^- ion proposed in reference 10 and in reactions between hydrogen and the CH radical discussed in reference 2. For each formation type it was assumed that the dissociation of the

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hydrogen molecules takes place only in an interstellar cloud passing a hot star, as proposed in reference 6. It is further assumed that the formation of H_2 occurs in the same manner on the surfaces of Platt particles as on classical grains. From this figure it follows that the H_2 abundance will be very low at normal densities of the interstellar gas if the Platt particles are responsible for the observed extinction and polarization. Otherwise, for classical grains and a value of π that is not too small, the abundance of the molecular hydrogen will be between about 10 and 90 percent at a density of some 10 hydrogen atoms cm^3 in an interstellar cloud.

Therefore, it is possible to decide the type of grains that are realized in nature from observations concerning the abundance of the interstellar hydrogen molecule. Unfortunately, direct observations of the H_2 molecule are not possible from the Earth because the absorption lines of the molecule lie in the ultraviolet and its emission lines lie in the far infrared. Thus, until observations are made from rockets or orbiting telescopes, indirect methods of determining the abundance of the interstellar H_2 must be found. One possibility follows from dynamic considerations. The discrepancy between the density observed in the Sun's vicinity and the density following from the force perpendicular to the galactic plane is examined in reference 4. The difference between these two values of the density is assumed to belong to the interstellar hydrogen molecule. A similar consideration was made in references 7 and 8, in which the K force was determined in small distances from the galactic plane by the density distribution perpendicular to the galactic plane and the velocity distribution of the interstellar gas. It was found from this and the observed density of the stars and the interstellar matter that an abundance ratio of molecular to atomic hydrogen as high

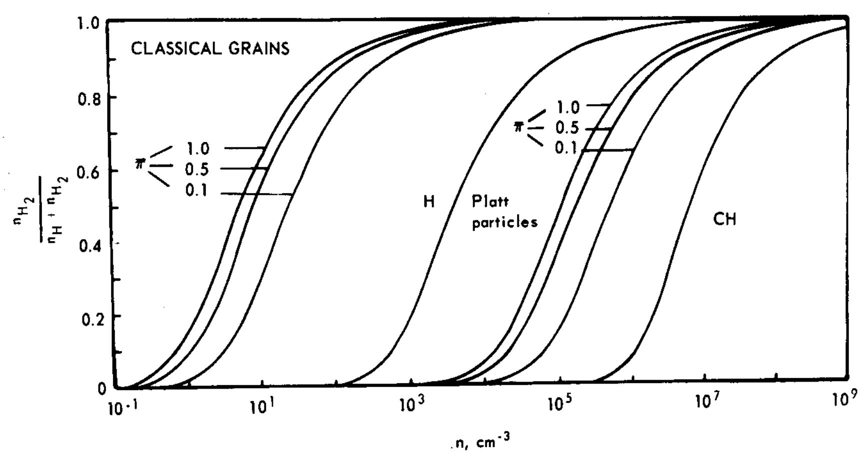

FIGURE 1.—Relative number density of hydrogen molecule in interstellar space for classical grains and Platt particles. $T = 100°$ K.

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as 4 or 5 is quite conceivable. The K force was determined in reference 11 by using the density distribution perpendicular to the galactic plane and the distribution of radial velocities of the interstellar gas and cepheids. The obtained K force is valid only for small distances from the galactic plane up to about 100 parsecs. Therefore, for the normal to the galactic plane $z > 100$ pc the result was fitted with the two K forces determined in references 12 and 13. The dependences of K with z obtained in this manner are called models I and II, respectively. By the aid of Poisson's equation and Maartin Schmidt's model of the galaxy, the density distribution was obtained perpendicular to the galactic plane. The uncertainties in Schmidt's model do not very strongly affect the distribution up to a value of z of about 400 pc. Figure 2 shows the dependence of the resulting density distribution on z for the K force (model I). The comparison between this curve and the density distribution curves of the observed stars and interstellar matter clearly shows an invisible component which is strongly concentrated to the galactic plane. Mainly this concentration leads to the supposition that the invisible matter is identical with interstellar H_2.

Now we shall examine whether or not the density distribution from the k force is compatible with an H_2 abundance following from a formation of the molecules on the surfaces of classical grains. The equilibrium density of H_2 between formation and dissociation near hot stars for classical particles is

$$n_{H_2} = 1.14 \times 10^{-2} \pi T_{gas}^{1/2} n_{HI}^{5/2}. \tag{2}$$

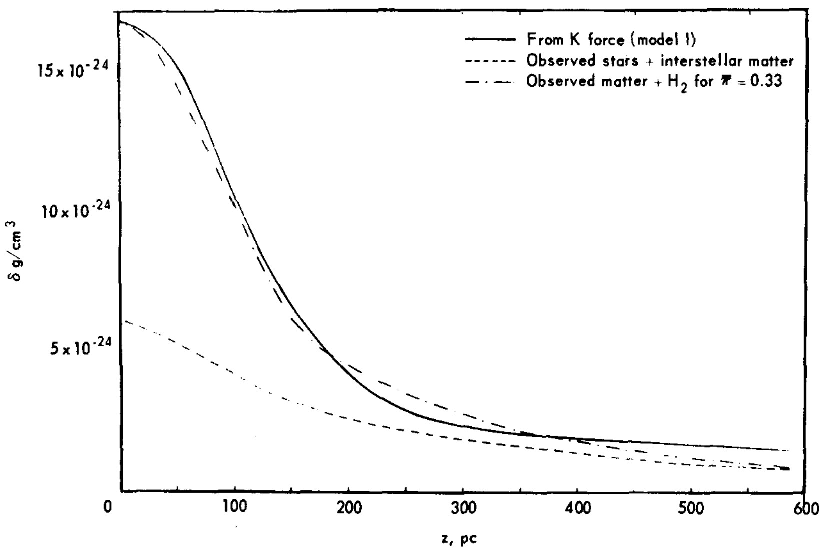

FIGURE 2.—Density distributions as function of z.

In order to get this equation, the relation between the density of dust and atomic hydrogen as stated in reference 14 was used:

$$\delta_{dust} \sim \delta_{\mathrm{HI}}^{3/2}. \tag{3}$$

Furthermore, the result found in reference 8 concerning the independency of the density ratio between molecular and atomic hydrogen on the distance from the galactic plane was applied. In order to get the H_2 density from equation (2), the density of the atomic hydrogen as a function of the distance from the galactic plane must be known. The interstellar matter is therefore assumed to be concentrated in clouds according to the model of reference 15. Therein the average radius is $\bar{r}=1.7$ pc, the distribution function of cloud radii is given by

$$\delta(r)=\frac{1}{\bar{r}}\,e^{-r/\bar{r}} \tag{4}$$

and the density inside a cloud is determined by the condition

$$rn_{\mathrm{HI}}=46\ \mathrm{pc/cm^3} \tag{5}$$

The observed hydrogen density perpendicular to the galactic plane from the 21-cm observations should be proportional to the number of clouds per unit volume. By the aid of these assumptions, the density of H_2 perpendicular to the plane was computed for a temperature $T_{gas}=100°$ K and for different values of the probability π. Then these density distributions of H_2 were added to the density distribution of the observed stars and interstellar matter and compared with the distribution following from the K force. There is a satisfactory agreement between the two curves for the probability $\pi=0.33$ at least up to 400 pc. From this it is concluded that the percentage of the interstellar molecular hydrogen is very large, about 80 percent. Clearly this value is not very certain and a value of 30 percent is also possible.

As has been seen from figure 1, this large content of H_2 is only possible if the formation of the molecules occurs on the surfaces of classical grains. It must therefore be concluded that mainly classical grains are responsible for the observed phenomena of the interstellar dust.

This conclusion is supported by the value of π. Values in the range 0.10 to 0.25 for the case of metal surfaces were found experimentally in reference 16. These values are for room temperatures. Some recent experimental work is reported in reference 17, in which a thermal beam ($T=80°$ K) of partially dissociated hydrogen was directed at a cooled copper surface; the reflection probability of the atomic hydrogen was measured as the temperature of the solid surface was lowered from 80° K to 3° K. They found that recombination occurred very efficiently when the temperature of the solid surface was between 10° K and 20° K. The agreement with our $\pi=0.33$ is satisfactory.

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DISCUSSION

Donn: Great care must be used in extrapolating the results of Brackmann and Fite to the interstellar problem. Although they found an anomalously high recombination coefficient between 15° K and 20° K, the conditions in their vacuum system and in interstellar space are most likely not equivalent.

I think it is also of interest to consider the formation of hydrogen molecules by a process other than surface recombination. If there are complex molecules in space, as a result of ejection from cool stars, atomic hydrogen may abstract a hydrogen atom from these hydrogen-rich molecules and form molecular hydrogen.

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